Numerical Modeling of Acoustic Propagation In a Variable Shallow Water Waveguide

Daniel Rouseff
Applied Physics Laboratory
College of Ocean and Fishery Sciences
University of Washington
1013 NE 40th St.
Seattle, WA 98105
phone: (206) 685-3078 fax: (206) 543-6785 email: rouseff@apl.washington.edu

Award Number: N00014-04-1-0148
http://www.apl.washington.edu

LONG-TERM GOALS

Random variability in shallow water will induce variability in a propagating acoustic field. The long-term goal of this research is to quantify how random variability in the ocean environment translates into random variability in the acoustic field and the associated signal processing algorithms. In the present funding cycle, the emphasis is on the effects of linear and non-linear internal waves on acoustic propagation in the mid-frequency (1-10 kHz) band.

OBJECTIVES

The specific objective for the current funding cycle is to understand the generation of new acoustic paths that occur due to the passage of non-linear internal waves.

APPROACH

During the Shallow Water 2006 Experiment (SW06), mid-frequency acoustic transmission data were collected over a continuous 7-hour period at range 550 m. The relatively short range was deemed desirable for isolating the effects of shallow water internal waves on acoustic propagation.

At the SW06 site, both linear and non-linear internal waves were potentially important. Linear internal waves often are modeled as a background random process introducing small changes in the sound speed that cause fluctuations in the acoustic field. At range 550 m, mid-frequency transmissions between 1 and 10 kHz were thought to span the transition between the regimes where classical weak- and strong-scattering theories for random media would apply [1]. Non-linear internal waves are often modeled as a more event-like process causing strong, localized changes in the sound speed. Packets of non-linear internal waves are not unusual and it was anticipated that a 550 m acoustic path might permit individual waves in the packet to be isolated.

Our approach is to use a statistical model for the acoustic fluctuations introduced by random background internal waves, and a more deterministic model for the acoustic effects introduced by passage of more event-like non-linear internal waves.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
Numerical Modeling Of Acoustic Propagation In A Variable Shallow Water Waveguide

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Washington,College of Ocean and Fishery Sciences, Applied Physics Laboratory,Seattle,WA,98105

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Random variability in shallow water will induce variability in a propagating acoustic field. The longterm goal of this research is to quantify how random variability in the ocean environment translates into random variability in the acoustic field and the associated signal processing algorithms. In the present funding cycle, the emphasis is on the effects of linear and non-linear internal waves on acoustic propagation in the mid-frequency (1-10 kHz) band.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**5**	

WORK COMPLETED

In the present funding cycle, the emphasis has been on analyzing acoustic data collected immediately before, during, and after the passage of a non-linear internal wave. The results show that new acoustic paths are generated and that these new paths are particularly strong as the non-linear internal wave passes above the acoustic source. The results have been documented in a refereed journal paper [Rouseff *et al.* 2008].

RESULTS

Figure 1 shows the positioning of assets at 20:53 UTC 18 August, 2006. The acoustic source was deployed off the stern of the *R/V Knorr* at depth 40 m. The depth was selected to keep the transmitter below a thin layer of warm, salty water that was present that day at depth 30 m. Of present interest are 20 ms duration linear frequency-modulated (LFM) chirp signals that were transmitted every 19 s. The signals were recorded at range 550 m using the MORAY moored receiving system. The system had two four-element vertical sub arrays with the bottom four elements (depths 50.0, 50.2, 50.5 and 51.4 m) being of present interest. While the acoustic data were being collected, investigators onboard the *R/V Oceanus* collected oceanographic data 250 m east of the *R/V Knorr* as a non-linear internal wave first approached and then passed the two ships. The wave subsequently passed MORAY. X-band radar measurements estimated the bearing and speed of the wave. Note that the bearing of the internal wave nearly coincided with the bearing from the R/V Knorr to MORAY. Consequently, the acoustic assets were well deployed to capture the passage of the wave. Additional oceanographic measurements included the water's temperature, salinity, density and turbulence dissipation rate [2]. Two acoustic Doppler current profilers (ADCP) were deployed to obtain vertical profiles of currents. A 120 kHz echosounder acoustically imaged the flow field.

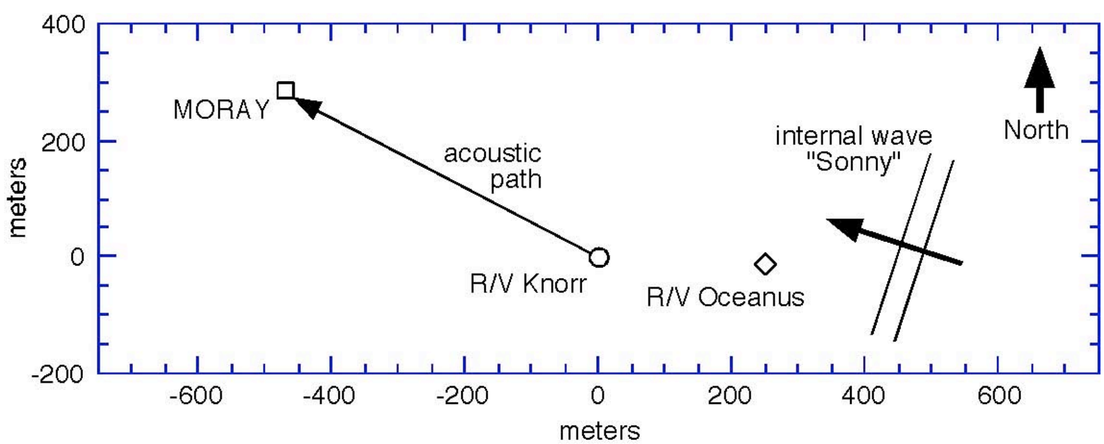

Figure 1. Experiment geometry. Acoustic source deployed off the stern of the R/V Knorr with transmitted signals measured 550 m away on MORAY vertical array. Oceanographic data collected on R/V Oceanus while a non-linear internal wave passed.

To understand the sequence of acoustic arrivals, the eigenrays from the source to different elements in the receiving array were calculated. The simulations suggested that the direct acoustic path to the receiver at depth 50 m was the most sensitive to the details of the sound speed profile; depending on

the particular profile used, the direct path might or might not fragment into multiple direct arrivals. The fragmented direct path might arrive before or after the path that bounced off the sea surface. Furthermore, the direct path might be stronger or weaker than the surface bounce path. The acoustic ray that was launched at a downward angle and bounced once off the seabed, however, was strong and stable and insensitive to the particular sound speed profile used in the simulation. Consequently, the initial analysis has concentrated on studying how the bottom bounce path changes as the non-linear internal wave passes between the acoustic source and receiver.

When the non-linear internal wave was in the vicinity of the *R/V Oceanus*, X-band radar measurements indicated the wave's bearing as 288 deg (Fig. 1) and its speed as 0.89 m/s. If the internal wave is modeled as a plane wave, these measurements are sufficient to estimate the wave's position as it passes the acoustic assets. Figure 2 is a waterfall plot showing how the acoustic arrival structure measured at depth 50 m changes in time. The matched filter output is plotted for 32 minutes of data include the periods immediately before, during and after the passage of the internal wave. The superimposed horizontal lines bracket the time when the peak internal wave displacement, passes between the acoustic source and receiver. The gross shifts in arrival time are due to relative motion between the source and the moored receiver. The bottom, bottom-surface, and surface-bottom bounce paths are labeled.

The most striking feature of Fig. 2 is the apparent generation of a new acoustic path as the internal wave passes above the acoustic source. The new path, circled in the figure as it appears, splits from the bottom bounce. At 21:21:13 UTC, approximately 3 minutes after the peak internal wave displacement has passed the acoustic source, the new path is at its strongest and its intensity exceeds the bottom bounce. Its arrival angle at 21:21:13 UTC is 12 deg and so steeper than the bottom-bounce path that precedes it. As the internal wave continues to move away from the acoustic source, the arrival angle for the new path continues to steepen but its intensity fades.

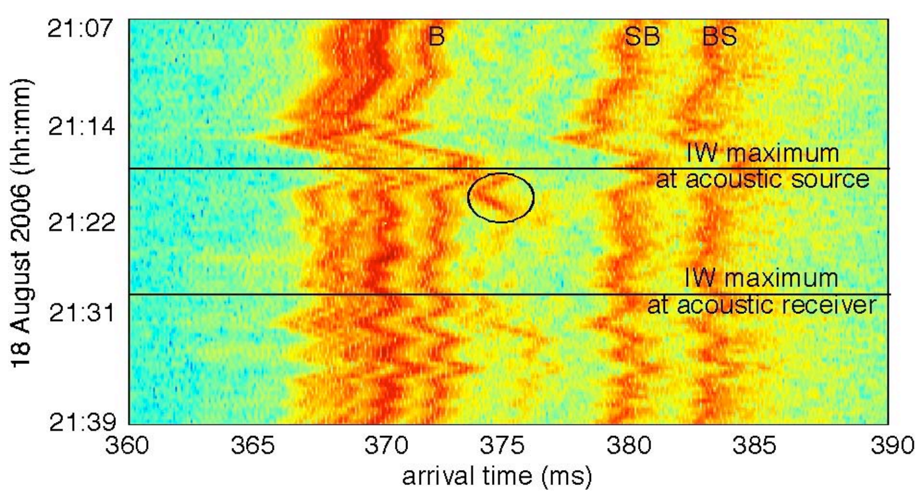

Figure 2. Time evolving acoustic arrival structure as the non-linear internal wave enters the acoustic propagation path. The bottom, bottom-surface, and surface-bottom bounce paths are labeled. New acoustic path (circled) is generated as the internal wave passes above the acoustic source. Red-green-blue color scale for acoustic intensity has 50 dB dynamic range.

We can develop a hypothesis for the new bottom-bounce ray observed in Fig. 2. The passing internal wave depresses the mixed layer and hence the sound speed profile. Since the acoustic source is below the mixed layer, an upward-launched acoustic ray will be refracted downward by the passing internal wave. The refracted ray passes through an upper turning point and then strikes the bottom further downrange than the original bottom-bounce path. After reflection, this new path arrives at the receiving array at a steeper angle than the unperturbed original bottom bounce.

To test the hypothesis, a series of range-dependent ray trace calculations were conducted. A simple soliton-based model for the internal wave [3] was implemented using parameters (wave amplitude, speed, and width; background sound speed profile) appropriate for SW06. The location of the internal wave between the acoustic source and receiver was then varied. Figure 3 shows a calculation with the peak internal wave displacement 250 m from the acoustic source. An upward launched ray is refracted downwards, reflects off the bottom, and is observed at range 550 m, depth 50 m. If the internal wave is displaced too far either towards the acoustic source or receiver then this path disappears. The simulation result is consistent with the experimental observation, Fig. 2.

Future work will involve both additional data analysis and modeling. The rest of the 7-hour acoustic data set, emphasizing the periods where non-linear internal waves were absent, will be processed. Individual acoustic arrivals will be studied as will groups of arrivals. Scintillation statistics and two-frequency correlation statistics will be complied and compared to models as appropriate.

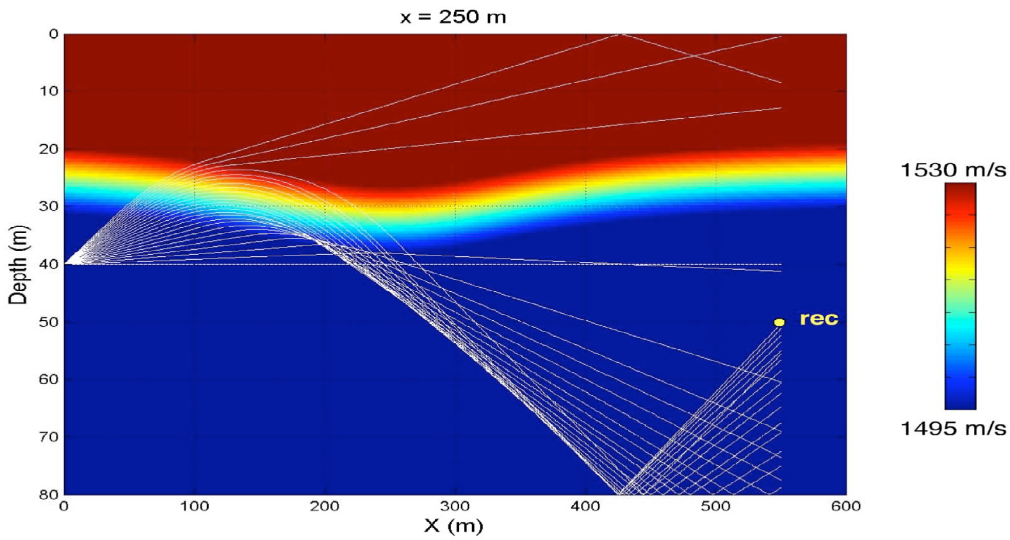

***Figure 3**: Ray trace through a passing non-linear internal wave. Peak internal wave displacement is 250 m downrange from the acoustic source. The internal wave causes refraction that results in a new bottom-bounce path that reaches the acoustic receiver at range 550 m and depth 50 m.*

IMPACT/APPLICATIONS

Internal waves are a ubiquitous feature of shallow water oceanography. Even when event-like non-linear internal waves are absent, random background internal waves will affect acoustic propagation in the mid-frequency regime relevant to Navy sonar systems. By studying data sets such as collected during the SW06 experiment, these effects can be quantified as a first step towards developing a predictive capability and possible mitigation strategies.

TRANSITIONS

Not applicable at this stage in the on-going research.

RELATED PROJECTS

Numerous ONR-supported investigators were involved in the SW06 Experiment and are analyzing the collected data.

REFERENCES

[1]B. J. Uscinski, *Elements of Wave Propagation in Random Media* (McGraw Hill, New York, 1977) pp. 69-77.

[2]E.L. Shroyer, J.N. Moum and J.D. Nash, "Observations of polarity reversal in shoaling non-linear internal waves," *J. Phys. Oceanogr*. (in press).

[3]J. C. Preisig and T. F. Duda, "Coupled acoustic mode propagation through continental-shelf internal solitary waves," *IEEE J. Oceanic Eng*. 22, 256-269 (1997).

PUBLICATIONS

D. Rouseff, D.Tang, K. L. Williams, Z. Wang, and J. N. Moum, "Mid-frequency sound propagation through internal waves at short range with synoptic oceanographic observations," to appear *J. Acoust. Soc. Am. Express Letters* (2008) [accepted, refereed].

D. Rouseff, M. Badiey, and A. Song, "Effect of reflected and refracted signals on coherent underwater acoustic communication: Results from KauaiEx 2003." *J. Acoust. Soc. Am.* [submitted].

D. Rouseff and W. L. J. Fox, "Energy consumption model for a broadband shallow-water acoustic communications network," to appear *IEEE J. Oceanic Eng.* (2008) [accepted, refereed].

J. E. Quijano, L. M. Zurk, and D. Rouseff, "Demonstration of the invariance principle for monstatic active sonar," *J. Acoust. Soc. Am.* 123, 1329-1337 (2008) [published, refereed].

L. Matveyev, R. C. Spindel, and D. Rouseff, "Forward scattering observation with partially coherent spatial processing of vertical array signals in shallow water," *IEEE J. Oceanic Eng*. 32, 626-639 (2007) [published, refereed].